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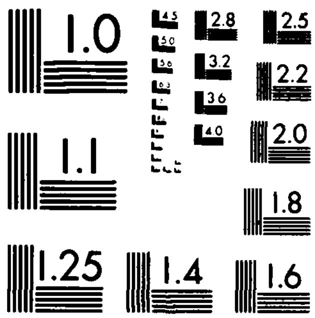
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Automatic Detection of Hail by Radar

PIO J. PETROCCHI

29 SEPTEMBER 1982

METEOROLOGY DIVISION PROJECT 6670
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An automated model algorithm for identifying hailstorms by radar is described. Hailstorms are identified by totaling seven weighted indicators based on a three-dimensional reflectivity structure of an ideal hailstorm. The weighting functions for each indicator and the total identifying the storms were determined by testing the algorithm with radar data that were verified by ground truth data. By use of these findings, the probability of detecting hail is 94 percent with a false alarm ratio of 6 percent for a critical success index (CSI) = 0.886 for this test sample.

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Preface

The author is indebted to Major Carlton L. Bjerkaas who suggested the concept of the hail algorithm, and to Mr. Steve Nelson of the National Severe Storm Laboratory (NASSL) who provided the ground truth hail verification data for this study. His thanks also to Mssrs. Ralph Donaldson and Kenneth Glover for guidance; Mr. Donaldson not only reviewed the report but suggested a number of very helpful improvements. Finally, the author thanks Mr. Aragam R. Nagesh of the Systems and Applied Sciences Corporation (SASC) for editing of the hail algorithm documentation included in the Appendix.

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Automatic Detection of Hail by Radar

1. INTRODUCTION

There has long been a need for an operationally effective means of distinguishing storms that produce hail. Over the years, radar meteorologists have been able to identify hail-producing cells with some success by examining radar returns for one or more storm characteristics such as echo tops, maximum reflectivities, heights of various reflectivities and tilt. Recently, Lemon[1] performed a study of the existing hail identification techniques; he derived a set of very successful severe hailstorm identification criteria for the WSR-57 radar based on the three-dimensional reflectivity structure of a model severe hailstorm.

The structural nature of the Lemon hail criteria suggested the development of a hail analysis algorithm for automated identification of hailstorms. The types of data required to test the conditions in the criteria are readily available in our existing Modular Radar Analysis System (MRAS).[2] In the course of development, we added six additional hail indicators to supplement the Lemon criteria. Four of these proved useful.

(Received for publication 29 September 1982)

1. Lemon, L. R. (1978) On the Use of Storm Structure for Hail Identification, Preprints, 18th Conference on Radar Meteorol., Boston, Am. Meteorol. Soc., 203-206.
2. Forsyth, D. E., Bjerkaas, C. L., and Petrocchi, P. J. (1981) Modular Radar Analysis Software System (MRASS), Preprints, 20th Conference on Radar Meteorol., Boston, Am. Meteorol. Soc., 696-699.

2. HAIL INDICATORS

Our nine hail indicators were formulated to determine the existence of radar reflectivity structural features generally associated with hail producing cells. These hail features are represented schematically in a model of an ideal hail cell (Figures 1 and 2).

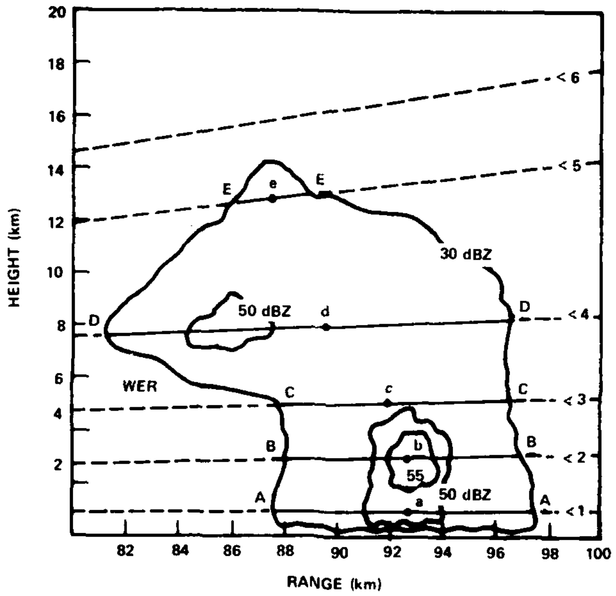

Figure 1. Vertical Cross Section of Radar Reflectivities in a Model Hailstorm

Descriptions of the nine hail indicators and the rationale for their use are presented as follows:

1. Mid-level (5 to 12 km reflectivity is at least 50 dBZ. Indicators 1 through 3 are almost direct adaptations of the Lemon criteria. Indicator 1 tests for a given reflectivity value in the mid-level regions. Lemon found from studies by Donaldson[3]

3. Donaldson, R. J. (1961) Radar reflectivity profiles in thunderstorms, J. Meteorol. 18:292-305.

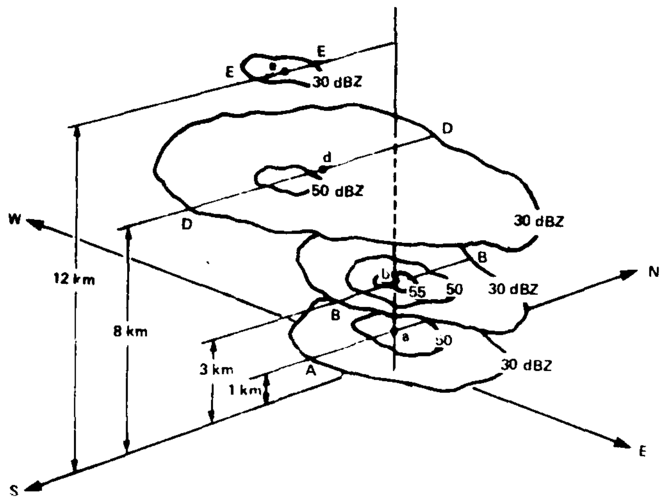

Figure 2. Radar Slice Schematic of the Model Hailstorm Shown in Figure 1

and Dennis et al[4] that the height of a given reflectivity is more significant than the peak reflectivity values for indicating the occurrence of hail. We found this to be so in our preliminary testing, but we increased the threshold value suggested by Lemon from 45 dBZ to 50 dBZ to decrease the number of false alarms.

2. Mid-level 30-dBZ contour extends at least 4 km beyond the 40-dBZ lowest level contour. Indicator 2 tests for the overhang of the mid-level echo over the edge of the low-level echo. This test checks for the existence of a weak echo region (WER) indicative of strong updrafts usually associated with severe hailstorms.[1] The WER is shown in Figure 1 as a region of reflectivity less than 30 dBZ located under a mid-level reflectivity contour that is at least 30 dBZ. As a result of our preliminary tests, we altered the extent of the overhang in the Lemon criteria from 6 km to 4 km.

3. The echo top lies over a mid-level overhang. Indicator 3 tests for the position of the echo top relative to the low level echo position. While indicator 2 tests for the existence of a persistent updraft at low levels, indicator 3 tests for its relative strength at upper levels. Lemon[1] concludes that if we have a strong updraft in a strongly sheared environment, we should find the top above the weak

4. Dennis, A.S., Smith, P.L., Jr., Boyd, E.I., and Musil, D.J. (1971) Radar Observations of Hailstorms in Western Nebraska, South Dakota School of Mines and Technology, Final Report, NSF Grant GA-1518, 42 pp.

echo region or above the overhang itself. These conditions are shown in our hail-storm model.

4. The maximum reflectivity at any level is at least 55 dBZ. Indicator 4 searches for a peak reflectivity value above a given threshold. This type of indicator has been used in the past with varying degrees of success.

5. The area of the 30-dBZ echo at any mid-level is at least 10 percent greater than the area of the lowest level 30-dBZ echo. It was the intent of indicator 5 to supplement indicator 2. From our hail model, it would appear that the area of a mid-level slice would always be larger than the area of a low-level slice.

6. The direction of tilt lies to the right of and/or behind the direction toward which the cell is moving. The direction of tilt is defined as the horizontal angle between the direction of the cell motion and a line directed through the centroid of a mid-level slice. A centroid is the calculated center of mass for a given slice as shown by lower case letters a, b, d, and e in the hail model. Indicator 6 supplements the test by indicator 3 and confirms the existence of a WER on the right or rear flank of a cell, as shown by the model hailstorm.

7. The 30-dBZ top is at least 8 km. Echo tops have long been used as a means of detecting hail. One problem is the selection of proper height thresholds which vary in different geographic regions and with the height of the tropopause. The combination of reflectivity threshold and height (30 dBZ, 8 km) was selected for the Oklahoma storms on the basis of preliminary tests.

8. The direction of tilt is towards the south. This test supplements the test by indicator 6. If we assume that most cells move in an easterly direction, this indicator tests for a cell tilt to the right of the cell direction as does indicator 6. Indicator 8 covers cases where the direction of movement for a given cell is unknown.

9. The movement of a cell is to the right or left of the mean motion of all cells. Indicator 9 was introduced as an experimental indicator to determine if hailstorms have a preferred direction of motion relative to the direction of motion of other storm cells.

3. ALGORITHM TESTS

The hail algorithm is one of four Special Analysis Modules (SAMS) operating under the Modular Radar Analysis System (MRAS).[2] The MRAS also preprocesses the radar data acquired during an antenna volumetric scan sequence and saves these data for use by the SAMs. The volumetric scan consists of a predetermined number of azimuthal scans at selected elevation steps. A typical volumetric scan sequence that we used for our data acquisition was composed of five 360° azimuthal scans at elevations of 0.2, 0.5, 1.5, 3.0, and 5.0 degrees.

Representations of the data acquired by the volumetric scan sequence are shown in Figures 1 and 2. The straight lines represent elevation radials that generate slices through a given cell. For each slice, the MRAS provides data defining the slice elevation angle, cross sectional area enclosed by the 30-dBZ reflectivity contour, coordinates of the weighted centroids (center of mass), maximum reflectivity, and the time of observation. For each cell, data are provided defining the maximum reflectivity, height of the cell's tallest slice, and the cell' speed and direction.

These acquired data are used by the hail algorithm to determine an assignme of one of three labels for each hail indicator. A "Y" is assigned if the conditions of the indicator are met; an "N" is assigned if the conditions are not met; finally, a "U" is assigned if the conditions of the indicator cannot be tested because of insufficient data. An insufficient data situation occurs when the predetermined volumetric scan sequence does not permit measurements above a required altitude.

A more detailed description of the hail algorithm is included in Appendix A.

4. TEST CONSIDERATIONS

The hail algorithm was tested on archived radar data obtained by a 10-cm radar in Oklahoma during the Joint Doppler Operational Project (JDOP).[5] Our test results were verified by ground truth data provided by S. Nelson of the National Severe Storm Laboratory (NSSL) from a ground observer network located west of the radar site. We tested data from nine selected days of diverse weather situation including a total of 206 observations. A valid observation required at least one of the two following conditions: A radar cell was identified within coverage of the ground observer network and/or a ground observer report was submitted of precipitation occurring during the period of radar operation.

For each observation, we performed our nine hail indicator tests. The outcome of each test and the associated ground report for the observation was used to classify the test into one of five categories: x, y, z, w, and u. Category x (successes), represented tests where the conditions of the indicator were met and hail was verified within an area defined by the 30-dBZ contour of the cell. The time constraint for hail verification required that the time of the reported event be within the period required to complete a volumetric scan which was typically 5 min. Time uncertainties reported by the ground observers were added to the time constraints. These uncertainties were generally less than 5 min. Category y (failures) represented

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5. JDOP Staff (1979) Final Report on the Joint Doppler Operational Project (JDOP) 1976-1978, NOAA Tech. Memo, ERL NSSL-86 Norman, OK, 84 pp.

tests where the conditions of the indicator were not met although hail was verified. Category z (false alarms), represented tests where the conditions of the indicator were met but hail was not verified. Category w represented tests where the conditions of the test were not met and hail not verified. Category u (unknowns), represented tests that could not be made owing to insufficient data.

We used the results of the tests to establish weighting functions for each of the nine hail indicators. Upon finding these functions, we were able to total a score for each observation that was a sum of the successful weighted indicators. We then used these scores to identify a given radar observation in one of four ways: a hailer, a probable hailer, a nonhailer, or an unknown.

5. WEIGHT DETERMINATION

We based our assigned weighting functions on the critical success index (CSI)[6] for each indicator. Donaldson defined the CSI as the ratio of successful predictions of a critical event to the sum of successful predictions plus unsuccessful predictions of both types. In terms of our test categories, we can express this as:

$$CSI = x/(x+y+z) . \tag{1}$$

The results of our tests were used also to determine probabilities of detection (PODs) and false alarm ratios (FARs).

The probability of detection is the proportion of hail events correctly predicted by the indicator test:

$$POD = x/(x+y) . \tag{2}$$

The false alarm ratio is the proportion of false indicator predictions of hail:

$$FAR = z/(x+z) . \tag{3}$$

A summary of the indicator tests and the calculated success indices are shown in Table 1.

It can be noted that test categories w and u are not used to determine the success indices. While the rejection of u is obvious, the rejection of w requires some clarification. It would appear that a prediction of no hail when in fact hail was not

6. Donaldson, R. J., Dyer, R. M., and Kraus, M. (1975) An Objective Evaluator of Techniques for Predicting Severe Weather Events, Preprints, 9th Conference on Severe Local Storms, Boston, Am. Meteorol. Soc., 321-325.

reported, constituted a success. The problem lies in the uncertainties in observing and reporting a hail event. Light hail can be easily masked when embedded in a heavy shower, or its occurrence can be missed if the edge of the hail falls a short distance away from an observer. In Table 1, we can see that w is large when compared with x + y + z. Uncertainties in w would overwhelm the meaning of any measure of the reliability of the hail identification technique which depends on w.

Another reason to ignore w is that the number of nonhail events greatly exceeds the number of hail events. One can envision the use of a very insensitive hail indicator to predict hail. If w were counted as a success, the overwhelming number of w's relative to a few failures to predict hail would result in a deceptive high CSI. Finally, any index involving w, even if w is measured accurately, would tell us more about the climatological occurrence of hail rather than the success of the hail identification method.

Table 1. Summary of the Indicator Tests and the Calculated CSIs, PODs, and FARs for 206 Observations

Indicator	1	2	3	4	5	6	7	8	9
x	36	30	10	47	16	26	8	34	20
y	1	2	1	9	21	11	0	5	19
z	5	8	1	37	8	10	2	7	25
w	101	92	88	113	99	70	79	87	25
u	63	74	106	0	62	89	117	73	117
CSI	0.857	0.750	0.833	0.505	0.356	0.553	0.800	0.739	0.312
POD	0.973	0.938	0.909	0.839	0.432	0.703	1.00	0.872	0.513
FAR	0.122	0.210	0.091	0.440	0.333	0.278	0.200	0.171	0.556

Although we recognize that the hail indicators are not totally independent parameters, they were treated as such by normalizing the CSIs to compute a weighting function W_i for each indicator i as shown by the expression:

$$W_i = \frac{CSI_i^2}{\sum_{i=1}^{N} CSI_i^2} \tag{4}$$

where N = the number of indicators.

This equation gives the highest weights to those indicators with the highest CSIs where the sum of all the indicator weights W_1 to W_n = 1. It should be noted that this technique does not maximize the PODs or minimize the FARs. The CSI is a parameter measuring the over-all effectiveness of our prediction and includes both the hail events that we failed to predict and our false alarms. It has a range of values from 0 to 1 with 1 being a perfect predictor and 0 meaning we haven't improved our prediction at all.

Listed in Table 2 are two sets of weighting functions for each hail indicator. The first set of functions was calculated from the CSIs determined in our tests. From these results we can see that indicators 5 and 9 are not useful as hail predictors because of their low CSIs. A second set of functions and the ones we finally used were calculated without indicators 5 and 9.

Table 2. Weighting Functions Determined From CSIs for Each Indicator

Indicator	1	2	3	4	5	6	7	8	9
Set 1	0.19	0.14	0.18	0.06	0.03	0.08	0.16	0.14	0.02
Set 2	0.20	0.15	0.18	0.07	....	0.08	0.17	0.15	....

6. TEST EVALUATION

These initial results show the relative validity of the nine hail indicators. An important comparison is one that we can make between the combined CSI of the first three indicators and the combined CSI of the parent WSR-57 hail criteria. We obtained a CSI of 0.813 compared to a CSI of 0.700 obtained by Lemon.[1] This apparent discrepancy can be attributed to the fact that two different criteria were used to verify the successful hail predictions. In the WRS-57 hail criteria evaluation tests,[1] a successful prediction required hail falls with stone diameters > 1.9 cm. No minimum size limitations were imposed to verify hail falls that were predicted by our hail algorithm which would in effect result in fewer false alarms and a better CSI value.

One of the unexpected results of the tests was the low effectiveness of the 55-dBZ reflectivity (indicator 4) as a dependable hail indicator. In another study by Dennis,[4] in Nebraska, high reflectivity provided an excellent indication of hail. We can attribute these conflicting results at least in part to climatological factors, as suggested by Donaldson.[6] Our data included many thunderstorms that produced heavy showers but no hail. High reflectivities detected in these storms resulted in false alarms that lowered the magnitude of the CSI. It should be noted, however, that the magnitude of the POD is still at an acceptable level and we should not underestimate the usefulness of this indicator.

Another result in question is the unrealistic POD value of 1.00 shown under indicator 7 (30 dBZ, 3 km). Unfortunately we did not obtain a large enough data sample to permit a completely reliable evaluation for this indicator. A shift of just one sample from a success to failure category would have had a large influence on the POD value. Our data sample was small because the heights of more than half of the total storms could not be determined owing to antenna elevation limits during data acquisition. We still feel, however, that this indicator is an excellent hail predictor.

Indicator 6 (the direction of tilt lies to the *right of and/or behind* the direction toward which the cell is *moving*) and indicator 8 (the direction of tilt is towards the south) are related in that they both test for the direction of storm tilt. Surprisingly, the tests show that indicator 8 is significantly better than indicator 6. In retrospect it appears that the conditions for testing indicator 6 were too restrictive, particularly in determining a tilt to the rear of the storm direction.

Of the nine indicators tested, 5 and 9 have CSIs below 0.500. We could not, of course, use these indicators in making the final hail determinations. However, they still remain in the hail algorithm for future test purposes.

7. HAIL IDENTIFICATION

We used the results of the indicator tests to formulate threshold values to identify a given radar observation. Our thresholds were determined by a scoring method described below.

Table 3. Truth Table Showing the Results of the Indicator Tests for Four Sample *Radar Observations*

Indicator	1	2	3	4	5	6	7	YSUM	NSUM	CF	SCORE	OBS ID
Weight	20	15	18	7	8	17	15	68	24			
Obs 1	Y	Y	Y	N	U	N	Y	68	24	92	74	HAIL
Obs 2	Y	N	N	Y	N	N	U	27	58	85	32	
Obs 3	Y	Y	U	Y	N	U	U	42	8	50	84	PROB
Obs 4	U	U	U	N	Y	U	U	8	7	15	53	UNKN

In Table 3, YSUM is the weighted sum of tests that have met their criteria (Y)s; NSUM is the weighted sum of tests that have not met their criteria (N)s. The (U)s are tests that could not be performed because of insufficient data; CF is the sum of YSUM and NSUM. Since CF is the maximum possible weighted sum for tests that could be performed for a given cell, we can consider CF as a Confidence Factor for that cell; CF = 100 if all of the tests are performed. A relative score (SCORE) is determined by a ratio of the sum of the successful tests to the total possible sum or

$$SCORE = (YSUM/CF) \times 100 \ . \tag{5}$$

After finding the SCOREs for each of the 206 observations in our tests, we endeavored to find the best SCORE thresholds that could identify storms with the highest probability of success. The CSIs, PODs, and FARs were calculated for ten ranges of the SCORE and for three ranges of the confidence factor (CF) as shown in Table 4. Once again, for each SCORE and CF range we define x as cells in which hail indicator conditions were met and hail confirmed; y as cells in which hail indicator conditions were not met but hail reported; z as cells in which the hail conditions were met but hail not confirmed; u as cells in which the hail indicator conditions could not be tested; and w as cells in which the indicator conditions were not met and hail not reported. The confidence level ranges were arbitrarily chosen to show the trend of success indices as the confidence level increases.

A comparison of the CSIs vs SCORE for the three CFs is shown by the graph in Figure 3. From the graph, we can see that the best threshold for identifying hailstorms for all three CFs is a SCORE that is at least equal to 60. We can also see that as the CF becomes greater we increase our CSI but lose some of our cell population. A good compromise for identifying hailstorms turns out to be a SCORE $\geq$ 60 with a CF > 50.

Figure 4 provides a flow diagram showing the required conditions for determining our four storm identifiers. Radar observations in which only 25 percent or less of weighted tests could be made (CF $\leq$ 25) are disregarded and labeled as unknown (UNKN). Remaining storms with scores $\geq$ 60 are labeled as hailer (HAIL) if CF > 50 or as probable hailers (PROB) if CF $\leq$ 50. Observations with scores < 60 are considered to be nonhailers. Going back and applying the hail algorithm to our data that included 206 radar observations, we obtained the results shown in Table 5.

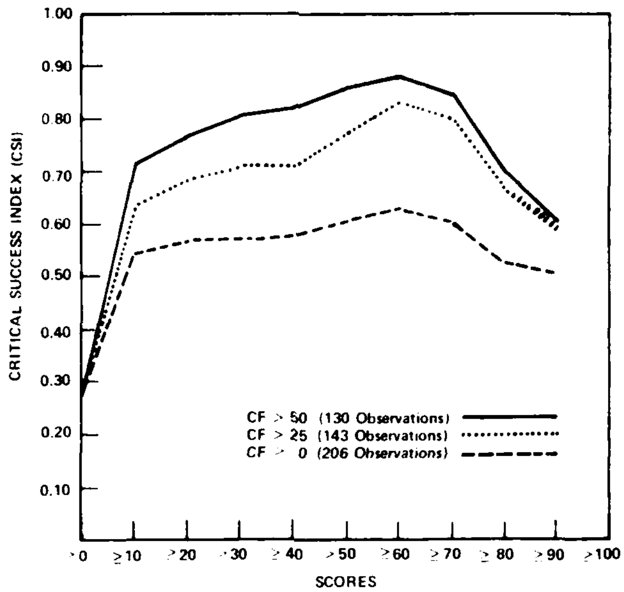

Figure 3. Variation of CSIs as a Function of SCOREs for Three Confidence Factor Ranges

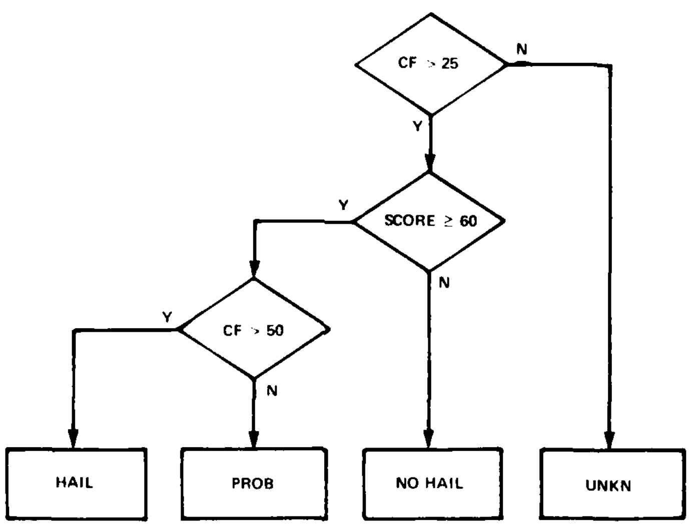

Figure 4. Conditional Flow Diagram for Identifving Hailstorms

Table 4. Hail Success Indices vs SCOREs for Three Confidence Factor (CF) Ranges

CF > 0										
SCORE	≥ 0	≥ 10	≥ 20	≥ 30	≥ 40	≥ 50	≥ 60	≥ 70	≥ 80	≥ 90
x	56	53	53	52	51	51	51	48	42	39
y	0	3	3	4	5	5	5	8	14	17
z	150	42	37	35	32	28	24	23	23	21
u	0	0	0	0	0	0	0	0	0	0
w	0	108	113	115	118	122	125	127	127	129
CSI	0.27	0.54	0.57	0.57	0.58	0.61	0.64	0.61	0.53	0.51
POD	1.00	0.95	0.95	0.93	0.91	0.91	0.91	0.86	0.75	0.70
FAR	0.73	0.44	0.41	0.40	0.39	0.35	0.32	0.32	0.35	0.35

CF > 25										
SCORE	≥ 0	≥ 10	≥ 20	≥ 30	≥ 40	≥ 50	≥ 60	≥ 70	≥ 80	≥ 90
x	37	37	37	37	35	35	35	32	26	23
y	0	0	0	0	2	2	2	5	11	14
z	106	21	17	15	12	8	5	3	2	2
u	63	63	63	63	63	63	63	63	63	63
w	0	85	89	91	94	98	101	103	104	104
CSI	0.26	0.64	0.69	0.71	0.71	0.78	0.83	0.80	0.67	0.59
POD	1.00	1.00	1.00	1.00	0.95	0.95	0.95	0.87	0.70	0.62
FAR	0.74	0.36	0.32	0.29	0.26	0.19	0.12	0.09	0.07	0.08

CF > 50										
SCORE	≥ 0	≥ 10	≥ 20	≥ 30	≥ 40	≥ 50	≥ 60	≥ 70	≥ 80	≥ 90
x	33	33	33	33	31	31	31	28	23	20
y	0	0	0	0	2	2	2	5	10	13
z	97	13	10	8	5	3	2	0	0	0
u	76	76	76	76	76	76	76	76	76	76
w	0	84	87	89	92	94	95	97	97	97
CSI	0.25	0.72	0.77	0.80	0.82	0.86	0.89	0.85	0.70	0.61
POD	1.00	1.00	1.00	1.00	0.94	0.94	0.94	0.85	0.70	0.61
FAR	0.75	0.28	0.23	0.29	0.14	0.09	0.06	0.00	0.00	0.00

Table 5. Hail Identification Summary and Success Indices for 206 Radar Observations

Cell Identifiers	Number of Observations Identified	Hail Occurrences	Failed to Detect Hail	False Alarms of Hail
Hailers	33	31	2	2
Prob Hailers	7	4	0	3
Nonhailers	103	2		
Unknowns	63	19		

Cell Identifiers	Successes (x)	Failures (y)	False Alarms (z)	POD	FAR	CSI
Hailers	31	2	2	0.939	0.061	0.886
Hailers and Prob Hailers	35	2	5	0.946	0.125	0.833

Out of 206 observations, the hail algorithm identified 33 cells as HAILERS. Only two of the identified HAILERS were false alarms and only two hail occurrences were not identified by the algorithm to give as a probability of detection (POD = 0.939, a false alarm ratio (FAR) = 0.061 and a critical success index (CSI) = 0.886. We were able to identify an additional seven PROBABLE HAILERS by using a lower confidence factor but we also increased our false alarms. When using the lower confidence factor we in effect improved our probability of detection to 0.946 but increased our false alarm ratio to 0.125 and decreased our critical success index slightly to 0.833. Out of the 103 observations identified as NONHAILERS, only two were reported as hailers. We did not use these observations to calculate our success indices because of the uncertainties in the reporting of nonsevere events but the correct identification of a NONHAILER is in fact a successful prediction.

All of the results of the most current analysis are stored on disc for subsequent call by the MRAS print and plot modules. Our print output lists the results of the analysis in a format similar to the one shown in Table 3. The plot output is dis-displayed on a CRT monitor in conjunction with the track output. In addition to other track information, each cell is annotated with a symbol H, P, U or a blank to indicate if the cell was identified as a hailer, a probable hailer, an unknown or a nonhailer, respectively, and the associated score.

8. CONCLUSIONS

We have shown that hailstorms can be automatically identified with a high degree of reliability by computer processing of real-time radar data. The advantages over the past hail identification techniques are twofold. First, the computer processing allows testing of many hail criteria. We were able to make at least nine tests without timing limitations. Although we did exclude two of our initial tests, the results indicate that our CSI increases as a function of the number of valid tests. Our second advantage lies in the nature of the automatic technique, allowing an analysis of every storm within the radars coverage area.

The only apparent limitations of the automatic hail detection technique is the data acquisition constraint by the elevation scan sequence. A typical scan sequence used to acquire the data for our study was composed of five elevations that included 0.2, 0.5, 1.5, 3.0, and 5.0 degrees. At a maximum elevation of 5.0 degrees, we could not measure tops of storms above 8 km when the ground ranges of the storms were less than 86 km. We were able to test storms within this range with other hail indicator tests but with less confidence.

In this study we were able to correlate storms producing hail without size distinction to a SCORE threshold resulting from successful indicator tests. A natural extension of this work would be to correlate also hail size to the magnitude of the SCORE. Recalling that the SCORE is actually a ratio of the positive tests to the total tests performed, we can use only SCOREs where 100 percent of the tests were performed to make a valid SCORE vs hail size correlation. In our study we found 93 observations in which 100 percent of the tests were performed but only 6 of these observations were hailers. We tried to correlate the SCORE of these observations to hail size but the results were inconclusive. Our inability to make the SCORE vs hail size correlation can be linked to our inability to make all of the indicator tests particularly in cells within 86 km.

It should be pointed out that the elevation scan sequence used to acquire our data has been designed with other objectives in mind. We intend to continue our hail studies using a tailored elevation scan sequence that will enable complete testing of more cells. One of the primary objectives of future studies will be to extend our hail identification capability to include a prediction of hail size.

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Appendix A

Hail Algorithm Description

A1. FUNCTIONAL DESCRIPTION

The purpose of this algorithm is to predict one of the following four cases:

- a given storm produces hail,
- a given storm probably produces hail
- a given storm does not produce hail,
- a given storm cannot be analyzed due to lack of insufficient data.

This algorithm analyzes storm data available in a specific format as described by the following. A storm is defined as a three-dimensional region of significant reflectivity values (≥ 30 dBZ). It is assumed to be made up of two dimensional circular storm components occurring at different elevation angles of radar observation. A storm component has associated with it, a centroid, a maximum reflectivity value and an area. The centroid is represented in a Cartesian coordinate system with the radar at the origin. The X-axis denotes east-west directions and the Y-axis denotes north-south directions. The maximum reflectivity value in a storm component is defined as the largest value of reflectivity obtained from the radar for the resolution volumes within the identified storm component. The area of a storm component is defined as the area of the circle representing the actual storm component. The centroid, the maximum reflectivity and the area for each storm component within a storm are obtained (refer to STORM STRUCTURE, NX-DR-03-009) as inputs to this algorithm. Additional storm parameters will be used as prime inputs. These are the estimated speed and direction of storm movement, the maximum reflectivity value within a whole storm, and the height of the storm's highest detectable storm component.

Two definitions are necessary to understand the process of analyzing the storm data. First is the overhang. A storm is said to have an overhang if the edge of the storm component at height between 5 km and 12 km extends beyond the edge of a storm component at the lowest elevation by at least 4 km. Second, a storm is said to have a tilt, if the centroid of a midlevel storm component is to the right or to the rear of the lowest level storm component.

Eight hail predictors are used to determine whether a given storm produces hail, will probably produce hail, or will not produce hail. A weight is associated with each predictor based on the empirical study of storms at AFGL. The predictors and their weights are:

1. The highest detectable storm component is at least 8 km. (Weight = 17)
2. The maximum reflectivity value within a storm is greater than 55 dBZ. (Weight = 7)
3. The centroid of the lowest level storm component is to the north of a centroid at any higher level (Weight = 15)
4. The direction of tilt is between 45 and 100 degrees to the right of the direction of storm movement. (Weight = 8)
5. The area of a storm component at any midlevel elevation is greater than that at the lowest elevation. (Weight = 0)
6. The maximum reflectivity in a storm component at midlevels (that is, 5 to 12 km heights) is at least 50 dBZ. (Weight = 20)
7. The overhang at the midlevel extends to at least 4 km beyond a lower level storm component. (Weight = 15)
8. The highest elevation storm component exists above a midlevel overhang. (Weight = 18)

The above predictors can be identified in two ways. A <u>positive</u> identification occurs when sufficient data exists to test for the presence of the corresponding condition associated with the predictor. Second, a <u>probable</u> identification occurs when sufficient data does not exist (for example, the radar could not take measurements beyond a fixed elevation angle). The algorithm tests for these two types of predictors and then computes two sums, one using only positive predictors and another using only probable predictors. The decision of labelling a storm as positively, probably, or not hail producing, or storm data is insufficient for hail analysis is then made as indicated by the procedure section.

A1.1 Source

This algorithm has been implemented by Air Force personnel at the Air Force Geophysics Laboratory (AFGL), Sudbury, Massachusetts

A1.2 Processing Environment

The HAIL algorithm is implemented as one of four special analysis modules that operate under the Modular Radar Analysis Software Systems (MRASS) (see Reference 2 in Section 1) implemented at AFGL, Sudbury. The algorithm requires outputs from the modules implementing algorithms described in STORM STRUCTURE (NX-DR-03-009), STORM FORECAST (NX-DR-03-008), and STORM CENTROIDS (NX-DR-03-005).

A2. INPUTS

A2.1 Identification

AREA	=	Areas of the storm components of an identified as given by STORM STRUCTURE (NX-DR-03-009).
DIRECTION	=	Direction of motion of each identified storm as given by STORM FORECAST (NX-DR-03-008). If the direction is not determined by STORM FORECAST, then its value is set as unknown.
ELEVATIONS	=	Elevation angles of each radar scan constituting one volume scan.
MAXIMUM STORM REFLECTIVITY	=	Maximum detected reflectivity value among all storm components of each storm.
SPEED	=	Speed with which each identified storm is moving as given by STORM FORECAST (NX-DR-03-008). If the speed is not determined by STORM FORECAST, then its value is set as unknown.
STORMS	=	Identifiers for three-dimensional regions characterized by a number of storm components taken at successive elevations and with reflectivity values above a given threshold.
STORM COMPONENT REFLECTIVITY	=	Maximum reflectivity value detected in an individual storm component.
STORM TOP	=	Altitude of the centroid of the highest detectable storm component in each storm. If the storm component is detected at the highest elevation angle the value is signed as a negative number.

TIMES	=	Observation times at the beginning of each radar scan, one for each elevation angle.
X-POSITION	=	X-positions of the mass weighted centroids (centers of mass) of the storm components observed at TIMES.
Y-POSITION	=	Y-positions of the mass weighted centroids (centers of mass) of the storm components observed at TIMES.
WEIGHT	=	Weight factor associated with each of the hail predictors identified in Section A1.

A2.2 Acquisition

AREA is acquired as an output from STORM STRUCTURE (NX-DR-03-009).
ELEVATIONS and TIMES are acquired directly as measured values from the Doppler radar.
SPEED and DIRECTION are acquired as outputs from STORM FORECAST (NX-DR-03-008).
STORMS are acquired as outputs from STORM CENTROIDS (NX-DR-03-005).
X-POSITION, Y-POSITION, STORM TOP, MAXIMUM STORM REFLECTIVITY, and STORM COMPONENT REFLECTIVITY are acquired as outputs from STORM STRUCTURE (NX-DR-03-009).
WEIGHT is a system supplied parameter whose value is based on the study of hail producing storms.

A3. PROCEDURE

A3.1 Algorithm

```
BEGIN ALGORITHM (HAIL)
1.0 COMPUTE (AVERAGE SPEED)
2.0 COMPUTE (AVERAGE DIRECTION)
3.0 DO FOR ALL (STORMS)
    3.1 IF (SPEED is unknown)
          THEN (Set SPEED to AVERAGE SPEED)
        END IF
```

```
3.2   IF (DIRECTION is unknown OR DIRECTION differs from
        the AVERAGE DIRECTION by 90° or more)
        THEN (Set DIRECTION to AVERAGE DIRECTION)
      END IF
3.3   IF (STORM TOP is not known)
        THEN (Identify probable HAIL PREDICTOR #1)
      END IF
3.4   IF (STORM TOP is at least 8 km)
        THEN (Identify positive HAIL PREDICTOR #1)
      END IF
3.5   IF (MAXIMUM STORM REFLECTIVITY is greater than
        55 dBZ)
        THEN (Identify positive HAIL PREDICTOR #2)
      END IF
3.6   COMPUTE (X-SPEED_
3.7   COMPUTE (Y-SPEED)
3.8   DO FOR ALL (ELEVATIONS)
      3.8.1  COMPUTE (RADIUS)
      3.8.2  COMPUTE (RANGE)
      3.8.3  COMPUTE (HEIGHT)
      END DO
3.9   DO (ELEVATIONS) FROM (Second lowest) TO (Highest)
      3.9.1  COMPUTE (X-DISPLACEMENT)
      3.9.2  COMPUTE (Y-DISPLACEMENT)
      3.9.3  COMPUTE (DELTA ANGLE)
      3.9.4  COMPUTE (DISTANCE)
      3.9.5  IF (Y-DISPLACEMENT is negative)
               THEN (Identify positive HAIL PREDICTOR #3)
             END IF
      3.9.6  IF (DELTA ANGLE is between 45 and 180 degrees)
               THEN (Identify positive HAIL PREDICTOR #4)
             END IF
      3.9.7  IF (RADIUS of current storm component is greater
               than RADIUS of lowest elevation storm component)
               THEN (Identify positive HAIL PREDICTOR #5)
             END IF
      3.9.8  IF (HEIGHT of the current storm component is not
               between 5 and 12 km AND STORM TOP is not known)
               THEN (Identify probable HAIL PREDICTOR #6)
               (Identify probable HAIL PREDICTOR #7)
             END IF
```

```
3.9.9  IF (HEIGHT of the current storm component is
         between 5 and 12 km AND STORM COMPONENT
         REFLECTIVITY is greater than 50 dBZ)
         THEN (Identify positive HAIL PREDICTOR #6)
       END IF
3.9.10 IF (HEIGHT of the lowest elevation storm component
         is less than 5 km AND HEIGHT of the current storm
         component is between 5 and 12 km)
         THEN COMPUTE (OVERHANG)
           IF (OVERHANG is greater than 4 km)
             THEN (identify positive HAIL PREDICTOR #7)
           END IF
    END DO
3.10 IF (HEIGHT of the last storm component is above the HEIGHT
       of the storm component that has the OVERHANG)
       THEN COMPUTE (STORM TOP DISTANCE)
         IF (STORM TOP DISTANCE is less than or equal to
           the RADIUS of the storm component that contains
           the OVERHANG)
           THEN (identify positive HAIL PREDICTOR #8)
         END IF
     END IF
3.11 IF (STORM TOP is not known)
       THEN (Identify probable HAIL PREDICTOR #8)
     END IF
3.12 IF (STORM TOP is unknown AND HEIGHT of the highest
       elevation storm component is less than 5 km)
       THEN (Identify probable HAIL PREDICTORS #2, #3, #4, and #5)
     END IF
3.13 COMPUTE (POSITIVE WEIGHT)
3.14 COMPUTE (PROBABLE WEIGHT)
3.15 COMPUTE (CONFIDENCE FACTOR)
3.16 IF (CONFIDENCE FACTOR is greater than 25)
       THEN COMPUTE (SCORE)
       ELSE (LABEL the current STORM as having insufficient data)
     END IF
```

3.17 IF (SCORE is less than 60)
THEN (LABEL the current STORM as a *non-hail producer*)
IF (CONFIDENCE FACTOR is greater than 50)
THEN (LABEL the current STORM as a hail producer)
ELSE (LABEL the current STORM as a probable producer of hail)
END IF
END IF
3.18 WRITE (LABEL)
END DO
END ALGORITHM (HAIL)

A3.2 Computation

A3.2.1 NOTATION

$\overline{S}$ = AVERAGE SPEED OF N storms in km/sec.

N = Number of storms whose speeds are known.

S_i = Speed of i^{th} storm from SPEED in km/sec.

$\overline{D}$ = AVERAGE DIRECTION of N storms in radians.

D_i = Direction of i^{th} storm from DIRECTION in radians.

SX_i = X-SPEED, X-component of the speed of the i^{th} storm in km/sec.

SY_i = Y-SPEED, Y-component of the speed of the i^{th} storm in km/sec.

R_{ij} = RADIUS of the storm component of the i^{th} storm at j^{th} elevation in km.

AR_{ij} = Area of the storm component of the i^{th} storm at j^{th} elevation in km^2 from AREA.

Pi = Mathematical constant having a value of 3.1416.

RC_{ij} = RANGE to the centroid of the storm component of the i^{th} storm at j^{th} elevation in km.

XC_{ij} = X-POSITION of the centroid of the storm component of the i^{th} storm at j^{th} elevation in km.

YC_{ij} = Y-POSITION of the centroid of the storm component of the i^{th} storm at j^{th} elevation in km.

H_{ij} = HEIGHT of the centroid of the storm component of the i^{th} storm at j^{th} elevation in km.

ϕ_j = The j^{th} elevation angle in radians available from ELEVATIONS.

dX_{ij} = X-DISPLACEMENT, relative distance in the X-direction between the location of the centroid of the i^{th} storm at j^{th} elevation and the location of the centroid of the i^{th} storm at lowest elevation in km.

dT_j = Time elapsed between radar scan at j^{th} elevation and radar scan at lowest elevation in seconds.

dY_{ij} = Y-DISPLACEMENT, relative distance in the Y-direction between the location of the centroid of the i^{th} storm at j^{th} elevation and the location of the centroid of the i^{th} storm at lowest elevation in km.

dQ_{ij} = DELTA ANGLE, the horizontal angle formed by a line from the centroid of the storm component of the i^{th} storm at j^{th} elevation and the centroid of the storm component of the same storm at lowest elevation to a line that is parallel to the direction of the storm's movement.

HD_{ij} = The horizontal DISTANCE between the centroid of the storm component of the i^{th} storm at j^{th} elevation and the centroid of the storm component of the same storm at lowest elevation in km.

O_{ij} = OVERHANG, the distance between the edge of the storm component of the i^{th} storm at j^{th} elevation and the furthest edge of the storm component of the same storm at lowest elevation in km.

OD_i = STORM TOP DISTANCE, the horizontal distance between the centroid of a storm component of the i^{th} storm at a midlevel altitude (5 km to 12 km) and the centroid of the storm component of the same storm at the highest elevation, in km.

PSW = POSITIVE WEIGHT, total weight of all the positive hail predictors identified.

PRW = PROBABLE WEIGHT, total weight of all the probable hail predictors identified.

POS = POSSIBILITY, a number indicating the measure of the probability of labelling a STORM to be a potential hail producer.

NOTE: This algorithm has been implemented on a 32-bit minicomputer.

A3.2.2 SYMBOLIC FORMULAS

COMPUTE (AVERAGE SPEED)

$$\overline{S} = \left[\sum_{i=1}^{N} (S_i) \right] / N$$

COMPUTE (AVERAGE DIRECTION)

$$\overline{D} = \left[\sum_{i=1}^{N} (D_i) \right] / N$$

COMPUTE (X-SPEED)

$$SX_i = (S_i)(\sin D_i)$$

COMPUTE (Y-SPEED)

$$SY_i = (S_i)(\cos D_i)$$

COMPUTE (RADIUS)

$$R_{ij} = (AR_{ij}/Pi)^{1/2}$$

COMPUTE (RANGE)

$$RC_{ij} = [(SC_{ij})(XC_{im}) + (YC_{ij})(YC_{ij})]^{1/2}$$

COMPUTE (HEIGHT)

$$H_{ij} = \left\{ (RC_{ij})^2 / [(2)(1.21)(6371)] \right\} + \left\{ (RC_{ij})(\sin(\phi_j)) \right\}$$

where 1.21 is the index of refraction and 6371 is the radius of earth in km.

COMPUTE (X-DISPLACEMENT)

$$dX_{ij} = XC_{ij} - (XC_{i(lowest)} + (SX_i)(dT_j))$$

COMPUTE (Y-DISPLACEMENT)

$$dY_{ij} = YC_{ij} - (YC_{i(lowest)} + (SY_i)(dT_j))$$

<u>COMPUTE</u> (DELTA ANGLE)

$$dQ_{ij} = [\tan^{-1}(dX_{ij}/dY_{ij})] - \overline{D}$$

<u>COMPUTE</u> (DISTANCE)

$$HD_{ij} = [(dX_{ij})^2 + (dY_{ij})^2]^{1/2}$$

<u>COMPUTE</u> (OVERHANG)

$$O_{ij} = HD_{ij} + R_{ij} - R_{i(lowest)}$$

<u>COMPUTE</u> (STORM TOP DISTANCE)

$$OD_i = [(dX_{i(mid)} - dX_{i(highest)})^2 + (dY_{i(mid)} - dY_{i(highest)})^2]^{1/2}$$

<u>COMPUTE</u> (POSITIVE WEIGHT)

PSW = Sum of the WEIGHT of positive HAIL PREDICTOR #i,
where i is index for positive predictors

<u>COMPUTE</u> (PROBABLE WEIGHT)

PRW = Sum of the WEIGHT of probable HAIL PREDICTOR #j,
where j is the index for probable predictors

<u>COMPUTE</u> (CONFIDENCE FACTOR)

CF = 100 - (PROBABLE WEIGHT)

<u>COMPUTE</u> (SCORE)

SCR = ((POSITIVE WEIGHT)/(CONFIDENCE FACTOR))*100

A4. INFERENCES

A4.1 Limitations

This algorithm is limited to three-dimensional reflectivity structure and assumes that all storm component are circular. To provide optimum results, the volume data should be acquired at elevation angles which permit sampling up to 8 km in altitude over the entire radar range.

A4.2 Future Developments

The algorithm is currently undergoing testing to optimize the WEIGHTs.